Space Policy 27 (2011) 89–93

Contents lists available at ScienceDirect

Space Policy

journal homepage: www.elsevier.com/locate/spacepol

Human space exploration and human spaceflight: Latency and the cognitive scale of the universe

Dan Lester [a,*], Harley Thronson [b]

[a] Department of Astronomy C1400, University of Texas, Austin, TX 78712, USA
[b] NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA

ARTICLE INFO

Article history:
Received 10 December 2010
Accepted 9 February 2011
Available online 18 May 2011

ABSTRACT

The role of telerobotics for space exploration in placing human cognition on other worlds is limited almost entirely by the speed of light, and the consequent communications latency that results from large distances. This latency is the time delay between the human brain at one end, and the telerobotic effector and sensor at the other end. While telerobotics and virtual presence is a technology that is rapidly becoming more sophisticated, with strong commercial interest on the Earth, this time delay, along with the neurological timescale of a human being, quantitatively defines the cognitive horizon for any locale in space. That is, how distant can an operator be from a robot and not be significantly impacted by latency? We explore that cognitive timescale of the universe, and consider the implications for telerobotics, human spaceflight, and participation by larger numbers of people in space exploration. We conclude that, with advanced telepresence, sophisticated robots could be operated with high cognition throughout a lunar hemisphere by astronauts within a station at an Earth–Moon L1 or L2 venue. Likewise, complex telerobotic servicing of satellites in geosynchronous orbit can be carried out from suitable terrestrial stations.

"It's the latency, stupid"
Stuart Chesire, "Wizard without Portfolio", Apple Computer, Inc.

1. Introduction

The contrast between human spaceflight, on the one hand, and human space exploration on the other, is critical and poorly understood. The former is essentially about launching astronauts into space. The latter is, as expressed by the MIT space policy group, about "an expansion of the realm of human experience", and may or may not require astronauts.[1] In the case of human spaceflight, it is largely just the astronauts whose realm of experience is being expanded. In the case of space exploration, it may be many more people, most of whom may never leave the Earth. This distinction is unsettling to many, as the concept of human exploration seems inextricably connected with "going there".[2] Bringing human experience to other worlds without bringing humans is the promise of telerobotics, and of what is called 'virtual presence'.

2. Telerobotics, virtual presence, and the importance of latency

The rapid advance of telerobotics, both commercial and scientific, prompts careful examination of the contrast between human spaceflight and human space exploration. Telerobotics is, in this sense, about an approach toward "virtual reality", and the extent to which a human being can visit and interact with another place without actually being there. That is no less than *human space exploration without astronauts*. There are several important aspects of human spaceflight that cannot be addressed in this way, for example human physiology in the space environment, and the potential medical benefits that such work brings back to Earth, if not an ultimate task of expanding humanity. But for the larger question of understanding and experiencing other places, the importance of physically being there is rapidly becoming less than it used to be. Technologically our capabilities in this area are in their infancy, although we have made great progress in high-bandwidth communication links, high-quality imaging sensors, and dexterous manipulators. These manipulators could be enhanced with haptic sensors that bring our sense of touch to other places as well. If we desire to duplicate human senses more completely, chemical sensors for smell and taste, and microphones for hearing could, in principle, also be added, although they may well not be necessary to the job that needs to be done. All these sensors and manipulators

* Corresponding author. Tel.: +1 512 471 3442.
E-mail address: dfl@astro.as.utexas.edu (D. Lester).

[1] MIT Space, Policy, and Society Research Group "The Future of Human Spaceflight" December 2008, http://web.mit.edu/mitsps/MITFutureofHumanSpaceflight.pdf.

[2] Lester, D. F., and Robinson, M. "Visions of Exploration", 2009 Space Policy 25, p. 236.

0265-9646/$ – see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.spacepol.2011.02.002

can bring our awareness and responsiveness to other places. Progress on such telerobotics is relentless, and advances in at least built-in autonomy and self-prediction routines can be expected to be well-represented by Moore's Law of exponential growth in digital switch density. Having astronauts assisted by telerobots was included in NASA's plans for Constellation and most recently expressed in the Enabling Technology Development and Demonstration Program, as well as the draft technology roadmaps from the Office of the Chief Technologist.[3] The expanded use of telepresence to achieve key goals in support of human space exploration was endorsed by the Augustine Committee.[4] Telerobotic exploration was a near-term goal for the Flexible Path strategy the committee considered a preferable option for space exploration.[5]

This article makes the case that a fundamental difference between telerobotics and astronauts on-site for space exploration is latency – the time delay between an event and its observation. It is not intended to be a human-versus-robot discussion, but rather what might be better posed as a humans-versus-space suits discussion; that is, how humans, at a site where they are not latency-limited, can most effectively experience and explore. Latency is, in many respects, the immutable savior of human spaceflight as rationale for human space exploration. Advances in telerobotics will include impressive autonomous abilities. These will be used for supervisory control with intelligent assistant software mitigating the latency in the interaction of human and robot, thereby extending our cognitive reach. Efforts on Robotnaut have been enabling in this regard.[6] But extending the senses and dexterity of a human being is a lot easier than duplicating in hardware the real-time decision-making power and common sense of a human brain. Latency is the property that truly constrains human telerobotic space exploration, or at least experience, of the cosmos. Indeed, when the latency is sufficiently low and telepresence sufficiently sophisticated, the experience of an astronaut on-site, encased within a constraining and sense-dulling spacesuit, is likely to be far less "real" than that of humans immersed in high-quality telepresence.

The importance of latency in planetary exploration has been addressed by a number of works. Spudis and Taylor offer a thoughtful assessment of telerobotics, and the importance of low latency for lunar science.[7] While they conclude that low-latency telepresence is not essential for science, high latency may lead the operator to concentrate more on the mechanical aspects of the work than on its intellectual aspects. In this respect, minimizing latency in telepresence may have value that goes beyond simple reduction of time to accomplish a task. Quantitative assessments of the impact of latency on exploration efficiency have been done using Earth-based exploration analogs. Snook et al. evaluated the fidelity of science tasks done in three ways – 1) shirt-sleeved human; 2) human in EVA suit; and 3) a "2015-class" telerobot with many-second latency, and they compared the time required in each case.[8] In this comparison, they found that the EVA-suited scientist could get things done about five times faster than this particular "telerobot", and the shirt-sleeved human could do it a lot faster. Of course, a shirt-sleeved human is irrelevant to most space exploration, but is an illuminating comparison. If they added more latency, corresponding to Earth-to-Mars, they estimated a factor of more like 25 between an on-site astronaut and an Earth-based telerobot. Furthermore, since a "2015-class" telerobot was, they thought, about ten times more capable than a "2002-class" telerobot, a space-suited human on Mars could perform work about 250 times more efficiently than the 2002-class telerobot on Mars controlled from the Earth. But if you reduce the latency, and possess a technologically more sophisticated robot, that factor will be reduced. Latency is by far the most important effect here in cognitive impediment.

In planetary science the importance of sample return is well understood. Humans on site can return with a large mass of samples, primarily because a return vehicle is a requirement for human exploration, and such a return vehicle must necessarily have a large mass and volume capability. If returning a large mass of samples is a major priority, there is no reason why a telerobotic explorer cannot have that capability.

The implications of this issue for the technology investment priorities of space agencies are profound. Space technology funding is under constant pressure with respect to, for example, on-going agency projects and programs. Thus, the challenge becomes whether increasingly limited funds will be invested to enable a tiny handful of humans (i.e. astronauts) to explore exotic worlds directly or whether those funds will be used to enable an alternative vision for exploration by a larger number of people via advanced telepresence. Space exploration advocates readily dismiss generic "astronauts versus robots" controversies; far less easily dismissed in many cases is "astronauts versus low-latency telepresence". In an era of limited funding, the latter may well be a higher priority to enable human space exploration.

3. Latency as dictated by the speed of light in space exploration

For space exploration, one sees that latency, otherwise more broadly known in the communications industry as "lag", "ping", or simply time delay, in this case limited by the speed of light, is what keeps virtual reality in space unrealized at an important level. For the Moon, the two-way latency is about 2.6 sec, even assuming that other elements of communication latency, such as serialization, packet switching, or queuing are kept to zero. You push a button in Pasadena and, at best, you see the shovel on the lunar bulldozer drop 2.6 sec later. On Mars, this may be 3 min or as many as 22 min! The quotation in the introduction to this paper by Stuart Chesire simply expresses the fact that latency, rather than bandwidth, can be the limiting feature of a communication channel when it comes to getting things done.

What telerobotics does is to put human consciousness and capability at places that may not be convenient, or even safe, for human beings. It can be not only about safety for human beings but, for the more difficult destinations, about making operations affordable there. What telerobotics does not do in space exploration is to feature personal courage, risk, and human endurance in obvious ways. These qualities of human brio are valued elements of a strong society. Although these qualities can be achieved in many other ways, for these reasons telepresence in space may never entirely replace human spaceflight as an important international endeavor. For example, telerobotics bears on space colonization and settlement, but only in the way it might help people move somewhere else. Such settlement and colonization might be of value, although has never been identified as a formal priority by any nation.

[3] NASA Robotics. Tele-Robotics and Autonomous Systems roadmap –http://www.nasa.gov/pdf/501622main_TA04-Robotics-DRAFT-Nov2010-A.pdf

[4] "Seeking a Human Spaceflight Program Worthy of a Great Nation: Review of Human Spaceflight Plans Committee", Office of Science & Technology Policy, 2009.

[5] Korsmeyer, D. et al. "A Flexible Path for Human and Robotic Space Exploration" at 2010 AIAA Space Operations 2010 Conference, 26–30 Apr. 2010, Huntsville, AL.

[6] Ambrose, R. et al. "An Experimental Investigation of Dextrous Robots Using EVA Tools and Interfaces", AIAA Space 2001 2001–4593.

[7] Spudis, P., and Taylor, G. "The Roles of Humans and Robots as Field Geologists of the Moon", in The Second Conference on Lunar Bases and Space Activities of the 21st Century, Volume 1 p.. 307–313 (SEE N93-17414 05-91) September 1992.

[8] Snook, K. et al. "Integrated Analog Mission Design for Planetary Exploration with Humans and Robots" he Roles of Humans and Robots as Field Geologists of the Moon", in 'The Geology of Mars: Evidence from Earth-Based Analogs', edited by M. Chapman, 2007, Cambridge University Press, pp. 424–455.

Some may contend that, with regard to capability, an *in situ* human cannot be replaced by a telerobot. That is, virtual presence can never displace feet on the ground or fingers in the regolith. Judgment, creativity, dexterity and precision can only come from human flesh on-site, and will never be transmitted over communication channels. But this is a lesson derived from historical terrestrial exploration and one that may not pertain anymore. It is rapidly becoming less true, a fact that is especially evident to a younger generation that has grown up with advanced communication and virtual-presence technologies. In any case, bulky space suits, helmets, gloves, and boots seriously inhibit any real experience of the environment and actually cause sensory deprivation.

Again, to the extent that exploration is about discovery and doing things, *being there virtually*, even with high latency, but with sensors that are far better than those on our own bodies, and manipulators that can operate more precisely and deftly than our fingers, will eventually eclipse astronauts being there physically. The evolution of exploration, driven by our newfound technological skills, is happening with astonishing rapidity. It is something that many have not yet recognized and may have a hard time accepting.

In many respects the role of telerobotics in the evolution of space exploration is reminiscent of the fear of automation 50 years ago, when inhuman machines made of wire and gears were going to replace dedicated craftsmen whose forefathers had passed on their deep wisdom to them. Their skilled hands and keen eyes would, no doubt, end up out on the sidewalk selling pencils. At that time the very idea that manufacturing by pairs of deft, but calloused, hands would largely be taken over by machines was both ludicrous and frightening. This is no longer so. We understand that those skills are still of value in creating and controlling these machines. Our cultural perspective on manufacturing evolved dramatically, as our cultural perspective on space exploration now must. As manufacturing by humans came to rely on human-controlled robots, so human exploration now appears to be evolving… and rapidly.

The way that latency affects teleoperation and telepresence is a well studied matter of cognitive neuroscience (see for example the reviews by Straube[9] and Bunge[10]). Mental chronometry, as it is termed, is about how response time in perceptual-motor tasks affects understanding of the content, time duration, and sequencing of cognitive operations. It is clear that cognitive operations are seriously affected as latency increases above a certain length of time. That limiting timescale, multiplied by the speed of light, can be termed the “cognitive scale of the universe”. It is the distance over which our real-time cognition – that is, real-time human thinking and mental response – can be effectively transmitted.

There is no question that humans have the ability to control telerobotics in spacecraft at large distances. The two Voyager spacecraft, now roughly a hundred astronomical units away, presenting a two-way latency of more than a day, are still being directed by dedicated (and patient!) human explorers back on Earth, and continuing their long list of accomplishments. These craft are considered our farthest reach in space exploration and have been labeled a “grand gesture of the Third Age of Discovery”.[11] But that latency delay is hardly matched to the cognitive abilities of these human explorers. They push the button, and wait, and wait …

This paper cannot adequately review the enormous amount of work in this field, which has examined the effects of latency on different functions. The impact of latency on perceptual-motor tasks depends strongly on exactly what one is trying to accomplish. Operation of the Voyager spacecraft is pretty simple, and hardly taxes human cognition, even at shorter distances. Other efforts could be far more challenging.

4. Cognitive timescales in space exploration

The cognitive timescale of the universe can be defined as the distance at which perceptual-motor tasks are equally limited by human neurophysiology, synaptic linkages and the speed of light. We can note a few relevant timescales.

- 20 to 40 ms — two-way neural signal transmission between brain and fingertip;
- 150 ms — recommended two-way maximum time delay for telephone service;
- 200 ms — human eye-hand reaction time;
- 300 to 400 ms — the blink of a human eye;
- 400 ms — time for the fastest American baseball pitches to reach the strike zone.

In particular, for online gaming, for which low latency is particularly critical, the two-way latency numbers are:

- 50 to 60 ms — limit of delay detection;
- 200 ms — delays becomes noticeable;
- 300 to 500 ms — games become unpleasant, even unplayable.

To these we can add experience from commercial activities that are increasingly reliant on telepresence. Robotic telepresence in mining equipment typically involves two-way latencies of no more than a few hundred milliseconds. For transcontinental surgery by telepresence, now widely accepted by the medical community, many surgeons can work successfully with a latency of 300 ms. Properly trained surgeons can even do precision surgical tasks with 500 ms of latency.[12] Piloting of military drone attack aircraft can involve two-way latencies of 1000–2000 ms, although those unimpressive latencies are dictated by being able to land, rather than to fly. The latter seems to be more forgiving of latency. The relevance of latencies to space exploration telerobotics has been investigated by a number of workers.[13,14,15,16,17]

Full haptic teleoperation, in which you do things by "feel" as well as by visual cues, requires some 100 ms latency or less. That is, getting information by feel on directionality and “slippage” needs fairly high performance. Low latency can thus provide a richly endowed situational awareness. Haptic (vibrotactile/force-feedback) sensors are considered to be generally useless for latencies of the order of 1 s or longer.

Clearly, the cognitive scale of the universe is going to be in this range of light travel time of the order of a few hundreds of

[9] Straube, B., Chattergee, A. “Space and Time in Perceptual Causality”, 2010 Frontiers of Human Neuroscience 4, 28.

[10] Bunge, M. “Causality and Modern Science” (1979, Dover).

[11] Pyne, S. “Voyager: Seeking Newer Worlds in the Third Great Age of Discovery” (2010, Penguin Group).

[12] Lum, M.J.H. et al. “Effect of Time Delay on. TeleSurgical Performance”, 2009 IEEE International Conference on Robotics and Automation, Kobe Japan, p. 4246, Paper SaC12.5.

[13] Sheridan, T. “Space. Teleoperation Through Time Delay: Review and Prognosis”, 1993 IEEE Transactions on Robotics and Automation, 9, 592.

[14] Wenzel, E. “The Role of System Latency in Multi-Sensory Virtual Displaces for Space Applications”, in “Usability Evaluation and Interface Design”, v1, p. 619 (2001, CRC Press).

[15] Lane, J. Corde, Carignan, C, and Akin, D. “Time Delay and Communication Bandwidth Limitation on. Telerobotic Control”, 2001 Proc. SPIE 4195, 405.

[16] Lane, J.C. et al. “Effects of Time Delay on. Telerobotic Control of Neutral Buoyancy Vehicles”, Proceedings of the 2002 IEEE International Conference on Robotics 8 Automation, Washington, DC, May 2002.

[17] Held, R., and Durlach, N. Telepresence, Time Delay and Adaptation” in "Pictorial Communication in Virtual and Real Environments" (1991, Taylor & Francis).

milliseconds. Again, we assume that we are limited entirely by light time, in that fast packet switching and dedicated communication systems can apply to space efforts. Of course, for many modern space communication systems such as NASA's Tracking and Data Relay Satellite System (TDRSS), where the conduit is shared, and bit rates for large files is more important than for small files, latency is less important than bandwidth.

Two-way light time latencies between relevant points in our Solar System are:

- 2600 ms Earth-to-Moon;
- 410 ms Earth–Moon L1 or L2–to-lunar surface;
- 240 ms Earth-to-GEO;
- 130 ms one side of the Earth to the other (circumferentially);
- 130 ms Deimos-to-Mars (Deimos is very roughly aereostationary).

It is clear from this and the cognitive timescales above that the distance from the Earth to the Moon is considerably larger than what we can call the cognitive scale of the universe, which is a very few hundred light milliseconds across. As a result, latency renders telerobots on the Moon controlled from the Earth somewhat less effective when short response times are important. That does not mean that we cannot teleoperate equipment in deep space from the Earth (as we do with Voyager); just that humans are not completely cognitively "on-site" when they do. At the other extreme, for example, we point out that with sophisticated telepresence and with regard to equipment operation, there is little obvious value for humans to be closer to a target site than light can travel in ~50 ms (~15,000 km): human perception and response is typically not much faster than this.

We are not suggesting the necessity of "total immersion" telepresence that would allow for a "virtual reality" experience. Not only are the technologies not yet available, but they are not necessary for enabling operation. Total sensory inclusion (smells of abraded rock, and the feel of dust falling on one's head, for example) is not particularly important for terrestrial mining, and is unlikely to be for most tasks in space.

5. Earth–Moon Lagrange points for cognitive control on the lunar surface

Of special importance here is the fact that Earth–Moon L1 or L2 libration points are just inside the cognitive horizon of the lunar surface. Earth–Moon L1, for example, is 61,500 km earthward from the Moon, about 16% of the Earth–Moon distance from the Moon. As a result, teleoperation of nearside lunar surface equipment, such as sample collection and inspection, mining and refining for in situ resource utilization (ISRU) [authors – please spell out this acronym at first use], and lunar base development, can be carried out capably via telerobots with nearly full cognition from astronauts orbiting L1. Such an Earth–Moon L1 orbit has been the subject of many concept studies for human space habitation. See, for example, the NASA Decadal Planning Team studies from 1999.[18,19] From these studies, Earth–Moon L1 is understood to be a credible and enabling near-term destination for human space travel.[20]

Not only is Earth-Moon L1 an enabling place for development, servicing, and depoting of equipment for cis-lunar space, it is also a site that contemporary EELV-Heavy launchers and habitat technologies should be able to support. Lunar nearside sites will generally have continuous coverage by telerobotic control from such an orbit, although the line-of-sight availability to the lunar poles will depend on the particular orbit. Although Earth–Moon Lagrange point operations figured prominently in the industry Concept Exploration and Refinement (CE&R) studies that predated the 2005 Exploration Systems and Architecture Study (ESAS), CE&R studies were largely ignored in what turned out to be the heavily lunar surface-centric Constellation architecture.[21]

We note that Earth–Moon L2 is similarly enabling for the lunar far side. That side does not allow direct telerobotic control from the Earth without a communication relay. While the South Pole Aitken basin on the far side is a key priority science target, the far side has many fewer such targets than the nearside (e.g. ESAS 4.3.6.3) however, and is not obviously a more optimal hemisphere for ISRU or outpost development. Orbital transfer from L1 to L2 is nevertheless straightforward (e.g. NASA's Artemis mission).[22] Of course, a low lunar orbit (LLO) could enable surface telepresence with considerably lower latency, but such orbits would lead to frequent and regular interruptions to telerobotic work at any one site as the control node rose and set. Moreover, depending upon the orbit, only a modest area of the Moon can be viewed.

For these reasons, Earth–Moon Lagrange points have been proposed as a "beachhead" for future human lunar surface efforts, much as Deimos, Phobos, or free orbit around Mars can be for eventual human efforts on the surface of Mars. To our knowledge, the first time this idea was suggested for Mars was in the "PH-D" (Phobos-Deimos) proposal by S. Fred Singer.[23] The idea was later broadly developed by a number of workers.[24,25] More recently, that idea has led to specific mission architectures, including Human Exploration using Realtime Robotic Operations (HERRO).[26,27] In the same way that human spaceflight to the lunar surface has been justified as providing practice opportunities for human spaceflight to the surface of Mars, so Earth–Moon Lagrange points can provide telerobotic construction practice for Mars.[28]

We note that the round-trip light-time latency between Earth and GEO is only about a quarter-second. Telerobotic operations in GEO could complement telerobotic efforts on the lunar surface from Earth–Moon Lagrange points, and feed-forward to telerobotics from Mars orbit. Moreover, advanced telepresence capabilities should in the near future allow complex robotic servicing operations on GEO

[18] Thronson, H., and Talay, T. "'Gateway' Architectures: a Major "Flexible Path" Step to the Moon and Mars after the International Space Station?" 2010 Space Review. http://www.thespacereview.com/article/1561/1.

[19] Garber, S., and Asner G. "NASA's Decadal Planning Team and the Policy Formulation of the Vision for Space Exploration", NASA History Program Office, see http://history.nasa.gov/DPT/DPT.htm.

[20] Lester, "First Stop for Flexible Path?" 2009 Space Review, http://www.thespacereview.com/article/1521/1.

[21] NASA Concept Exploration and Refinement (CE&R) studies – see http://www.nasa.gov/missions/solarsystem/vision_concepts.html.

[22] Woodard, M., Folta, D, and Woodfork, D. "ARTEMIS: The First Mission to the Lunar Libration Orbits" 21st International Symposium on Space Flight Dynamics, Toulouse 2009.

[23] Singer, S. "The PH-D Proposal: A Manned Mission to Phobos and Deimos," AAS 81-231, S. Fred Singer, The Case for Mars, Penelope Boston, editor, 1984, pp. 39–65; paper presented at the Case For Mars conference, Boulder, Colorado, April 29–May 2, 1981.

[24] Landis, G.A. "Robots and Humans: Synergy in Planetary Exploration" 2004 Acta Astronautica 55, 985.

[25] Burley, P.J. et al. "An Opposition Class Piloted Mission to Mars Using. Telerobotics for Landing Site Reconnaissance and Exploration" 2001 AIP Conf. Proc 552, 115. Space Technology and Applications International Forum.

[26] Podnar, G., Dolan, J., and Elfes, A. Telesupervised Robotic Systems and the Human Exploration of Mars" Journal of Cosmology, 2010, Vol 12, 4058-4067.

[27] Schmidt, G., Landis, G., and Oleson, S. "Rationale for Flexible Path – A Space Exploration Strategy for the 21st Century" 2010 JBIS 63, 42.

[28] Elfes, A. et al. "Safe and Efficient Robotic Space Exploration with. Tele-Supervised Autonomous Robots" Proceedings of the Association for the Advancement of Artificial Intelligence Spring Symposium, March, 2006, p. 104.

satellites that otherwise would be possible only by astronauts on site, which would be far more expensive than telerobots.

Earth–Moon Lagrange points are, because of the very small delta-V required to move from there to other Lagrange points in the Solar System, of great value as "job sites" for construction and servicing of assets that will be operated beyond cis-lunar space. Construction and servicing of large telescopes that would operate at Sun–Earth L1 or L2, construction of Mars ships, as well as a depot site for emplaced supplies, perhaps from extracted lunar resources destined for use farther in the Solar System are examples of this. Such a "job site" would benefit dramatically from sophisticated telerobotic controls. These controls could be used by astronauts within the habitat to telerobotically operate agents in free space outside the Lagrange point habitat with near zero latency and no EVA, as well as for lunar surface activities.

We also note that telerobotics will have an important role for use by humans who are physically on the lunar surface and controlling surface agents just outside their habitats. These humans may not want to do a lot of EVA work. But lunar surface telerobotics from a Lagrange point site offers significant cost advantages compared to putting people down on the lunar surface. Putting a hand on a joystick at Earth–Moon L1 is cheaper and easier than putting a hand on a joystick on the nearside lunar surface. In any case, the line-of-sight distance on the lunar surface is small, roughly 10 km for an antenna that is 50 m tall, so the range of such a lunar surface telerobotics node would be modest.

One challenge of extended telerobotic operation from an L1 habitat is radiation mitigation. Radiation is widely recognized as a – perhaps *the* – limiting natural barrier to long-duration human space flight beyond the immediate vicinity of the Earth. It is beyond the scope of this paper to discuss this issue. However, we note that designs for libration-point operations propose at present a mixture of short-duration habitation to limit human exposure and use of the crew transfer vehicle and/or a well-shielded habitat central core as a shelter in the event of a major solar storm.

It is worth pointing out that these latencies – Earth–Moon L1-to-Moon, Earth-to-GEO, and Deimos-to-Mars – are all in the range of current commercial terrestrial telepresence applications, such that commercial investment in terrestrial hardware and software as well as human training applies directly to telerobotic space exploration. Sufficiently motivated, space agencies can take advantage in the near term of vast investments in telepresence, telerobotics, and high-bandwidth communication that derive from terrestrial applications.

6. Conclusions

The cognitive scale of the universe for humans appears limited to a maximum of about 50–70,000 km, corresponding to round-trip speed-of-light latencies of 300–400 ms or less. Doing work at sites in space that demand full human cognition and challenging perceptual-motor capabilities means that people must be at least that close to the work being done. Of course, a dedicated communications link is also necessary, in order to avoid having to do heroic network optimization, in addition to careful data prioritization. We point out here that Earth–Moon L1 is such a site with regard to the lunar nearside. That latency is also roughly comparable to delays that will be experienced in telerobotics from Deimos to the surface of Mars. Such presence in Mars orbit may be the goal of our first human visits to the environs of that planet. Similarly, low-latency telerobotics from Earth to the many valuable assets in geosynchronous orbit could enable affordable sophisticated servicing.

While putting humans within the cognitive horizon of a site such as the lunar or Martian surface is hardly trivial, we believe that it can be done more economically than landing them on the surface. For early exploration at diverse sites, technology demonstrations, and pre-positioning of equipment that would later be used by humans on the surface, putting humans nearby in free space, such as at a lunar Lagrange point, or on a Martian moon, could be a useful approach.

Finally, this scale of latency is comparable to that being dealt with routinely for terrestrial telerobotics, in which the delays are largely not caused by light time, but by shared communication channels. A latency of a few hundred milliseconds, which bounds what we term the cognitive universe is also thus a "sweet spot" of sorts, for which supporting terrestrial technology investments will yield impressive return. For this reason, the Earth–Moon Lagrange point should continue to be considered a high-value near-term destination for human spaceflight.